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Title: Decentralized supply unit for selective and combined production of electrical energy, heat, and cooling, driven by external heat input.

[Abstract:]

The supply unit operates as a Stirling engine the operating piston (22) of which cooperates with a generator (90), for producing electrical energy. A heat pump circuit which operates according to the Vuilleumier principle can be switched-in via a dosing valve, which valve may in particular be in the form of a cylindrical slide valve (70). When the slide valve (70) is closed, the engine operates in a pure Stirling mode, for supplying electricity. When the slide valve is fully open, the engine operates in a pure Vuilleumier mode, which supplies heating or cooling. When the slide valve is in intermediate positions, mixed-mode operation occurs, providing heating, cooling, and electricity, in adjustable proportions.

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Claims:

1. A decentralized supply unit for selective and combined production of electrical energy, heat, and cooling,
comprised of a Sterling engine the operating piston (22) of which cooperates with a generator (90), for producing electrical energy,
and further comprised of a heat pump circuit including the operating piston (22) and operating according to the Vuilleumier principle, which heat pump circuit can be switched-in and which is regulatable with respect to its energy contribution.

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2. A supply unit according to claim 1; characterized in that it is configured as a free-piston engine.

3. A supply unit according to claim 1 or 2; characterized in that the operating piston (22) is part of an electric generator.

4. A supply unit according to claim 3; characterized in that the generator is a linear generator (90).

5. A supply unit according to one of claims 1 to 4; characterized in that the switching-in of the Vuilleumier heat circuit occurs via a regulatable dosing valve which is disposed in the heat circuit.

6. A supply unit according to claim 5; characterized in that the dosing valve is continuously adjustable from a closed position, which is associated with pure Stirling engine operation to supply electrical energy, through intermediate positions for proportional mixed mode operation, to an open position which is associated with pure Vuilleumier operation to supply heating and/or cooling.

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7. A supply unit according to claim 5 or 6; characterized in that the dosing valve is a cylindrical-element slide valve having a cylindrical valve element (70) which is preferably disposed axially in alignment with the cylindrical bushing (54) of the operating piston (22).

8. A supply unit according to one of claims 1 to 7; characterized by an electrical linear drive (92) which drives the supply unit in a pure Vuilleumier operating mode.

9. A supply unit according to claim 8; characterized in that an exciting coil of the linear drive (92) acts on the displacement piston (20) of the engine.

10. A supply unit according to one of clams 1 to 7; characterized in that, in a mode of operation very close to a pure Vuilleumier process the unit is self-starting and self-operating (self-maintaining).

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[Specification]:

There is increasing worldwide opposition to power plants fueled by combustion of fossil fuels, because of substantial environmental pollution and the relatively low efficiency by which is supplied to consumers. Other drawbacks of centralized energy supply are the high distribution costs and the blight to the appearance of the landscape caused by high tension lines. Also the distribution of heat from central heating facilities (waste heat from power plants requires high investment costs. Further, centralized supply of energy with associated large distribution networks has the disadvantage that disturbances to the power plants or distribution networks can lead to large-scale system failures.

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Accordingly, there is a need for a small energy supply unit which has high mechanical and thermal efficiency and allows one to produce electrical energy and heat energy in a decentralized fashion with virtually any desired source means, so that the high investment costs for distribution networks and high distribution losses are obviated. The energy supply unit ought to be environmentally benign, i.e. have low emissions of noise and pollutants.

A unit for supplying heating, cooling, and electrical current, in combination, based on the Vuilleumier process, is known from Ger. OS 33 02 553. This unit can serve for heating, air conditioning, and electricity supply of dwellings, businesses, and factories. The supply unit has two heat circuits with a respective differential piston in each circuit. The differential pistons are mechanically coupled via a crankshaft and connecting rod mechanism. Each of the differential pistons defines three cylinder spaces, wherewith in each case there are two heat withdrawal cylinder spaces of different size. In operation, on the heat withdrawal side between the smaller and larger cylinder spaces which are

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interconnected, there forms in each case a differential pressure which is utilized for driving an electrical generator. The differential pressure can be reduced by opening of a regulating valve. When the regulating valve is open, a purely Vuilleumier heat pump process takes place, and when the regulating valve is closed a proportion of the energy is drawn off for electricity supply.

Because of the fact that the pistons are mechanically coupled, and that three cylinder spaces are defined for each piston, this known supply unit is relatively costly to fabricate. Also, the Vuilleumier heat pump operation is the primary mode, and the electricity supply can be switched-on only proportionally and secondarily. Thus the unit does not allow full variability as to the type and proportion of the energy delivered; in particular, pure production of electrical energy is not possible, or is possible only at a low degree of thermal efficiency.

According to the state of the art, Stirling engines are also known, as are free-piston Stirling engines. The latter are attributed to William T. Beale, who developed this engine type in the early 1960s at Ohio University, Athens, OH, USA.

The underlying problem of the invention is to devise a decentralized supply unit driven by external heat input which provides the greatest possible variability in individual and combined generation of electrical energy, heating, and cooling, in a low-friction, low-wear configuration which is inexpensive and has high efficiency.

This problem is solved by a supply unit comprised of a Stirling engine the operating piston of which cooperates with a generator, for generating electrical energy,
and further comprised of a heat pump circuit including the operating piston and operating according to the Vuilleumier principle,
which heat pump circuit can be switched-in and which is regulatable with respect to its energy contribution.

Because of the external heat input, the inventively employed Stirling engine offers a free choice of energy media. The heat generation can be accomplished by combustion of

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liquid, gaseous, and solid fuels. Heat from sources such as, e.g., the sun, geothermal sources, or nuclear reactions is also a possibility. The capital cost of heat exchange means for the heat source is low. In the case of combustion, heat exchange is continuous, with heat input at a constant, high temperature. This enables a high thermal efficiency. Further, the combustion can be

conducted at constant pressure, in particular normal pressure, and with any desired amount of excess air. Emission of pollutants is low, e.g. nitrogen oxides emissions are less than 1/10 those attainable with explosion engines.

Because of its closed operating cycle, with a nearly sinusoidal pressure curve and the absence of strongly impinging valves, the Stirling engine is distinguished by nearly vibration-free, low-noise operation. The oscillations of the operating piston, displacement piston, and housing of the engine are such that the common center of gravity of these elements remains stationary; the engine thus has kinematic compensation. As a result of the hermetic sealing of the operating circuit, the Stirling engine is protected from dirt and is easy to maintain.

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Other advantages are advantageous starting behavior, particularly of the free-piston Stirling engine, and high thermal efficiency at partial load.

Also, the Vuilleumier heat pump circuit is distinguished by a substantially higher efficiency than attainable by customary heat pumps driven by electric motors. One should take into account the fact that the electrical energy needed to drive such electric motors is generated in a conventional thermal power plant and undergoes transmission losses, thereby providing overall efficiency of at best 30%. The decentralized direct combustion in a unit which has low noise and low pollutant emissions is much more efficient and desirable. The Vuilleumier heat pump has the advantages (which, as mentioned, also apply to the Stirling engine) of external heat input, particularly external combustion, and a closed gas circuit. It is equally well suited for operation as a heating apparatus or a cooling apparatus, and in particular can be used in a flexible manner for heating and air conditioning of a building.

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The inventive supply unit combines the advantages of a Stirling engine for generation of electricity and a Vuilleumier heat pump. Pure Stirling operation is possible, wherein electricity and heat (the latter as waste heat) are produced. Pure Vuilleumier operation is also possible, wherein the supply unit functions only as a heating and cooling unit. Finally, mixed operation is possible by partial switching-in of the Vuilleumier circuit, wherein electricity, heating, and cooling can be provided in arbitrarily selectable proportions. In all modes of operation, the supply unit operates in a highly environmentally benign manner, with external heat input, particularly by external combustion. The supply unit may have only a single closed gas circuit, which makes it relatively inexpensive to fabricate.

In a preferred embodiment of the invention, the supply unit is in the form of a free-piston engine. The free-piston technology employs no crankshaft, swash plates, cams, or other means for mechanical coupling and mechanical force delivery to or from the pistons of the operating engine.

There are no

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wear-generating transverse forces on the pistons, thus one can employ dynamic gas bearing lubrication, with no liquid lubricants. The pistons oscillate on gas cushions, with low friction and low wear; the spring force of the gas cushions is utilized, and the movement of the pistons depends solely on gas pressure changes. Accordingly, the free-piston engine has a very simple mechanical structure and correspondingly low fabrication cost. Moreover, it has lesser sealing problems than, e.g., conventional Stirling engines; it operates very reliably, with very long maintenance intervals, and is practically noiseless. The efficiency of the free-piston engine is c. 65%, which is very close to the ideal efficiency of a Carnot cycle. The free-piston technology offers the possibility of achieving efficiencies similar to those achieved in conventional large power plants, but here in a relatively small or even very small unit.

Another feature of the invention is the direct coupling of the the operating piston of the supply unit with an electrical generator, e.g. in the form of a linear generator. This makes it possible to convert engine movement directly into electrical energy. The losses are low and the efficiency is high.

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The Vuilleumier heat circuit can be switched-in in particularly simple and economical fashion via a dosing valve which is provided in the heat circuit. In particular, the dosing valve can be continuously adjustable from a closed position associated with pure Stirling operation for electricity generation, through intermediate positions for proportional mixed operation, to an open position associated with pure Vuilleumier operation for heating and/or cooling. Thus, the proportions of the individual types of energy are regulated in a simple manner via the opening cross section of a valve, which parameter can be conveniently and accurately adjusted. In a particularly practical embodiment which has advantages relating to fabrication, installation, and cost, a cylindrical slide valve is provided in the cylinder space of the Stirling engine, which valve is preferably oriented coaxially to the operating piston.

In pure Vuilleumier operation, the supply unit does not produce mechanical energy (or produces only minimal mechanical energy), so

that as a rule external drive means for the pistons are needed. These drive means are preferably provided in the form of an electrical linear drive. It is possible to use, e.g., the linear generator coupled to the Stirling engine, in reverse mode as

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a linear motor (linear drive means). However, for reasons of simplification of connections and switching, it is more practicable to provide a separate electrical linear drive for pure Vuilleumier operation, wherewith in particular an exciting coil can act on the displacement piston of the Stirling engine. It is also possible to operate the supply unit in a self-starting and self-maintaining mode which is very close to pure Vuilleumier operation, wherewith one optimizes the system dynamics in particular by suitable adjustment of the piston surfaces.

Additional features and advantages of the invention will be apparent from the following description of an exemplary embodiment of the invention, with reference to the drawings, which drawings are to some extent schematic. The exemplary embodiment should not be deemed in any wise limitative of the scope of the invention; in particular, any other embodiment other than an embodiment employing free-piston technology may be admissible.

Fig. 1 is a longitudinal cross section through a supply unit according to the invention;

Figs. 2a-2d illustrate the operating cycle of the supply unit, an appreciable part of which is represented schematically by a circuit diagram; and

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Fig. 3 is a block circuit diagram of the supply unit, including its electrical part.

With reference to Fig. 1, the inventive supply unit has a housing 10 with an external heat insulation shell component 12. On the upper side of the housing 10 is a Stirling head 14 with an oil or gas burner 16 as an external heat source for input of the energy needed for operating the supply unit. In the interior of the housing 10 there is disposed a piston-and-cylinder unit limited by the wall 18, with operating regions for two pistons, namely a displacement piston 20 and an operating piston 22. The two pistons (20, 22) are each associated with a thermodynamic operating circuit in which a fluid is transported through heat exchangers (24, 28; 34, 38) and a regenerator (26; 36) disposed between the heat exchangers. The operating circuits are fluidically coupled and are hermetically sealed with respect to the exterior. The operating medium may be, e.g., helium, at a pressure between c. 10 and 50 bar, which is charged one time into the cylinder.

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The supply unit according to Fig. 1 is an implementation of free-piston technology. The two pistons (20, 22) are thus not coupled by gear transmissions or other conventional mechanical coupling means, and no mechanical energy is withdrawn from the pistons. Rather, as will be further described hereinbelow, the operating piston 22 may comprise part of an electrical linear drive, whereby movement is converted directly into electrical energy; and also the displacement piston 20 may be moved via an electrical linear drive. In addition, the pistons (20, 22) oscillate only on gas cushions, wherewith the spring force of these cushions is exploited; and the pistons are moved exclusively by gas pressure changes.

The cylinder space of the piston-and-cylinder unit is divided into two axially adjacent sections by a dividing wall 40, one of which sections serves as the excursion space for the displacement piston 20 and the other as the excursion space for the operating piston 22. A guide rod 42 is held in place at the dividing wall 40, which rod extends axially in the center of the cylinder space. In the embodiment illustrated, the guide rod is rigidly attached to the dividing wall 40. However, a structure is possible in which the guide rod 42

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oscillates in the motor housing. The displacement piston 20 and operating piston 22 are both hollow pistons. Each has a respective inner hollow cavity (44, 46) which has, e.g., a rectangular cross section. The cavity 44 of the displacement piston 20 is connected to the piston end face directed toward the operating piston 22 via a central axial bore 48. The cross section of the axial bore 48 is narrower than that of the cavity 44, so as to form a neck-like narrowing. The guide rod 42 penetrates the axial bore 48 with seal means. The displacement piston 20 is axially displaceably borne on the guide rod 42. A gas volume enclosed in the cavity 44 is compressed by the guide rod 42 which acts like a piston in this sense, providing a buffer effect in the nature of a gas spring.

Entirely similarly, the operating piston 22 is spring-loadedly borne on the guide rod 42. The associated cavity 46 is adjoined by a central axial bore which leads to the end face of the operating piston 22 which end face is directed toward the displacement piston 20. A bearing bushing 50 is disposed in the axial bore, which bushing extends beyond the end face of the operating piston 22. The guide rod 42 penetrates this bearing bushing and acts like a piston on

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a gas volume disposed in the cavity 46, which gas volume acts like a gas spring.

The segment of the cylinder space in which the operating piston 22 operates has an appreciably wider cross section than the segment of the cylinder space in which the displacement piston 20 operates. In the exemplary embodiment illustrated, the wall 18 of the cylinder space has an outwardly curved part which begins at approximately the altitude of the dividing wall 40 and expands radially with progression toward the operating piston 22, until it reaches the outer wall of the housing 10. This wall section delimits an expansion space 52 in the thermodynamic operating circuit of the operating piston 22. The operating piston 22 is guided in a cylindrical bushing 54 the free width of which is appreciably smaller than that of the expansion space 52 and which is disposed centrally and axially in the interior of the cylinder space. Between the outer shell of the cylindrical bushing 54 and the outer wall of the housing 10 there are disposed:

-- the heat exchangers (34, 38) which are part of the operating circuit of the operating piston 22, which heat exchangers are disposed in a ring-shaped configuration; and

-- the regenerator 36, also ring-shaped, disposed between said heat exchangers.

The lower part of the housing 10 is occupied by a large-volume compression space 56 which

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provides the final part of the operating circuit of the operating piston 22. The cylindrical bushing 54 extends for a certain distance into the compression space 56, and terminates at a distance from the bottom of said space.

The operating piston 22 is shown in a central position in Fig. 1, whereas the displacement piston 20 is shown at the upper end point of its excursion. Correspondingly, an expansion space 58 which functions in the operating circuit of the displacement piston 20 has its minimum volume. The expansion space 58 is delimited by a hemispherically curved end face of the cylinder space, and correspondingly the upper end of the displacement piston 20 facing away from the operating piston 22 also has a generally hemispherical shape. The expansion space 58 communicates with a heating space 24 in the Stirling head 14 which is disposed axially symmetrically as a ring-shaped space on the dome of the cylinder. The heating space 24 is heated to a temperature of, e.g., c. 600 °C, by the hot gases of the burner 16. It represents the heat exchanger on the hot side of the thermodynamic operating circuit involving the displacement piston 20. Beneath the heating space 24 there adjoin the regenerator 26 and a cold space 28 of this same operating circuit, which cold space represents the heat exchanger

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on the cold side. The regenerator 26 and cold space 28 are each coaxially disposed on the outer side of the cylinder. In the lower region of the cold space 28, the cylinder wall is provided with a ring-shaped array of openings 64 by which the cold space 28 communicates with a compression space 66. The compression space 66 is a part of the displacement piston operating circuit. It is delimited by a flat end face of the displacement piston 20.

The dividing wall 40 is provided with maximally large throughgoing openings through which the compression space 66 of the displacement piston 20 communicates with the expansion space 52 of the operating piston 22. It is possible to completely eliminate the dividing wall 40, because other, dynamic solutions are possible within free-piston technology.

On the radially widening part of the cylinder wall 18 below the dividing wall 40, a cylindrical slide valve is disposed, the valve member of which is a cylindrical slide member 70 disposed coaxially to the cylinder axis. The guiding and sealing of said slide member are indicated schematically by an

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encircling collet 72 on the outer side of the cylinder. The diameter of the slide member 70 corresponds to that of the cylindrical bushing 54. The slide member can be displaced axially in the direction of the arrow 74. It can be completely withdrawn from the cylinder space, to enable unimpeded gas circulation. If it is slid completely into the cylinder space, so that its end comes to rest against the cylindrical bushing 54, it blocks all gas circulation in the operating circuit of the operating piston 22. The slide member 70 may alternatively be positioned in an intermediate position, allowing a desired amount of gas flow cross section; a representative such intermediate position is shown in Fig. 1.

The heat exchanger 28 on the compression side of the displacement piston 20 and the heat exchanger 34 on the expansion side of the operating piston 22 are in a common cooling circuit, e.g. a cooling water circuit. Member 76 is a cooling water connection for a water jacket 78 which surrounds the cold space 62 of the displacement piston circuit. A line 80 contained in the housing 10 leads from the water jacket 78 to the heat exchanger 34 of the operating piston circuit, which in turn has an outwardly leading

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connection 82. The cooling water circuit is closed by a connecting line 84 which connects to at least one heat exchanger 86 for removal of useful heat. The cooling circuit may be employed in particular

for building heating or hot water heating. Its operating temperature may be, e.g., c. 60 °C. Various other configurations for the dispositions and connections of the heat exchangers may be employed other than those illustrated.

The compression side of the operating piston circuit is at a lower temperature, which may be, e.g., c. 0 °C. This temperature is brought about in another circuit 88 which contains the compression-side heat exchanger 38 of the operating piston circuit.

The circuit 88 may have a configuration analogous to that of a customary heat pump circuit, and may withdraw heat energy at low temperature from the ground, e.g. from ground water or the like. Also the circuit 88 may be in the form of a cooling circuit, which delivers usable cooling to the surroundings, e.g. for air conditioning purposes. In such a case the operating temperature of circuit 88 preferably is set slightly lower, e.g. at -10 °C.

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Thus the inventive supply unit has a hot temperature zone, a warm temperature zone, and a cold temperature zone. Energy is supplied to the system primarily from the hot side, namely by continuous external burning of oil or gas in the burner 16. It will be appreciated that other fuels may be employed, and that in general any heat sources may be employed, in a flexible manner. The continuous external burning may be carried out with any desired amount of excess air, in a regime which gives off only modest amounts of noxious substances and odors.

The electrical part of the inventive supply unit, not illustrated in Fig. 1, is represented in Fig. 3. It enables the kinetic energy of the operating piston 22 to be utilized in an electric generator. In the preferred free-piston technology, the operating piston 22 may be a part of an electrical linear generator 90. The linear generator converts the kinetic energy of the operating piston 22 directly into electrical energy, with low losses.

In addition, an electrical drive means 92 is provided which, in the exemplary embodiment illustrated,

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acts on the displacement piston 20, and is suitable for driving said piston in oscillating (reciprocating) motion. This introduces energy into the supply unit. However, such a linear drive is not mandatory. Rather, the inventive supply unit can operate in a self-starting and self-maintaining manner in a mode very close to that of a pure Vuilleumier process. The linear drive 92 and the linear generator 90 are each provided with exciting coils so that the

adverse effects of the machine dynamics can be minimized by fully compensating action. The linear drive 92 for the displacement piston 20 may require 0-5% of the generator power.

As mentioned, the thermodynamic displacement piston circuit and the operating piston circuit are coupled by a flow connection between the compression space 56 of the displacement piston and the expansion space 58 of the operating piston.

These spaces together form a unitary cylinder space, which is connected to the other cylinder spaces (52, 66) via the regenerators (26, 36), so that in each partial volume (ignoring flow losses) the same pressure of the working gas prevails at any time. The regenerators (26, 36) withdraw

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heat during the transport of gas from a given hotter part into a given colder part; and when the gas flow is in the opposite direction from a given colder part to a given hotter part they supply heat to the working gas.

The displacement piston 20 and operating piston 22 reciprocate at a phase difference of c. 90°, which is developed from the mass distribution and pressure ratios, particularly in the gas spring volumes. After a sufficiently high temperature difference develops, the engine can start automatically or with a weak external impulse, e.g. with the use of the linear drive 92. The oscillation of the operating piston 22, displacement piston 20, and housing of the motor is such that the common center of gravity of these elements remains stationary. This results in noise-free and vibrationless operation, and a particularly advantageous direct energy generation in the electrical linear generator.

The operating cycle of the supply unit is illustrated in Fig. 2. For a simple appreciation of the functional sequence, suppose, e.g., the phase of the displacement piston precedes that of the operating piston by $\pi/2$ (although other phase relations are possible). In Fig. 2a the operating piston 22 is

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at the lower reversal point of its excursion. The displacement piston 20 leads the operating piston 22 by about 90°, wherewith it begins to force the hot gas from the expansion space 58 into the compression space 66. This gives rise to an underpressure in the compression space 66 because more gas is present in the cold region of the system. The pressure forces drive the operating piston 22 in upward acceleration. In this phase, heat is still being drawn off into the heat exchanger 34.

Fig. 2b shows the piston position which is also shown in Fig. 1. The operating piston 22 has moved upward into an intermediate position, pushing working gas from the middle cylinder space into the compression space 56. The displacement piston 20 is at its upper reversal point, and has completely forced the hot gas from the expansion space 58 into the compression space 66.

In Fig. 2c the operating piston 22 is at its top reversal point (top dead center point). The displacement piston 20 is 90° ahead of this, in its intermediate position, where it is forcing cold working gas via the cooler 28, regenerator 26, and heater 24 into the expansion space 58. The resulting increase of pressure causes the operating piston 22 to be accelerated downward.

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Finally, in Fig. 2d, the displacement piston 20 has been moved downward to its lower point of reversal (bottom dead center point). The operating piston 22 is on the way to its lower reversal point, from which it will be accelerated back upward as a result of underpressure in the gas spring space 46, and as a result of the underpressures in the cylinder spaces 66 and 56, 58 brought about by the displacement piston 20.

The inventive supply unit can be configured and controlled via the cylindrical slide valve 70 in such a way that two different fundamental engine types are realized. If the slide valve is closed, the engine is a Stirling engine which serves to generate electrical energy, with the piston 20 functioning as a displacement piston and the piston 22 functioning as an operating piston. The pressure variations established in the motor housing, which serve to drive the operating piston 22, are approximately sinusoidal. The kinetic energy of the operating piston 22 is partially converted into electrical energy by an electric generator, e.g. in the form of the linear generator 90.

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In contrast, if the slide valve 70 is fully opened, the inventive supply unit operates like a pure Vuilleumier engine in a free-piston configuration. Heat and coldness are generated, but not mechanical or electrical energy. The engine instead requires an input of external operating energy, advantageously supplied via the linear drive 92. As mentioned supra, the supply unit can be configured so as to operate in an autonomous manner self-maintaining), by a slight deviation from a pure Vuilleumier process, wherewith the engine itself will then provide the small amount of mechanical energy needed. The Vuilleumier engine operates as a heat pump; thus can it can be used for heating or cooling.

If the slide valve 70 occupies an intermediate position, the

manner of operation realized is between the extremes of the Stirling engine and the Vuilleumier engine. The kinetic energy of the operating piston 22 is partly utilized in the electrical generator and partly in the heat pump section. The respective energy components can be regulated by appropriate shifting of the slide valve 70. Thus, depending on demand, one can easily change to generate electrical energy, heat, or cooling. The electrical energy can be produced at efficiencies of greater than 40%.

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The use of helium as a working gas enables good efficiency even at low temperatures, which is not achievable with customary heat pumps.

Accordingly, the invention makes it possible, in the form of a very compact unit, to meet the demand for heating, cooling, and electricity in a home or apartment building or small or medium-sized business. The described supply unit may be used without technical modifications for cold storage facilities, home heating, and hot water heating. The invention makes it possible to provide cooling at quite low temperature and at the same time provide industrial process heating at quite high temperature.

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